2

Radionavigation System User Requirements

The requirements of civil and military users for radionavigation services are based upon the technical and operational performance needed for military missions, transportation safety, and economic efficiency. For civil aviation and maritime users, and for military users in missions similar to civil users (e.g., en route navigation), the requirements are defined in terms of discrete “phases of navigation.” These phases are categorized primarily by the characteristics of the navigation problem as the mobile craft passes through different regions in its voyage. For example, ship navigation becomes progressively more complex and risky as the ship passes from the high seas, into the coastal area, and finally through the harbor approach and to its mooring. Thus, it is convenient to view each segment separately for purposes of analysis. Phases of navigation are not as applicable to land transportation, due to the greater flexibility afforded land users to assess their position. Requirements will differ depending upon what the user intends to do, the type of transportation system used, and the user location within that particular transportation system.

Unique military missions and national security needs impose a different set of requirements that cannot be viewed in the same light. Rather, the requirements for military users are more a function of the system’s ability to provide services that equal or exceed tactical or strategic mission requirements at all times in relevant geographic areas, irrespective of hostile enemy action. All users require that systems used for safety service must be adequately protected.

In the discussion that follows, both sets of requirements (civil and military) are presented in a common format of technical performance characteristics whenever possible. These same characteristics are used to define radionavigation system performance in Section 3.

2.1 Civil Radionavigation System Requirements

The radionavigation requirements of civil users are determined by a DOT process that begins with acknowledgment of a need for service in an area or for a class of users. This need is normally identified in public safety and cost/benefit need analysis generated internally by the operating administration, from other Federal agencies, from the user public, or as required by Congress. User conferences have often highlighted user needs not previously defined.

In transition planning, radionavigation system replacement candidates must be reviewed in terms of safety and economic performance. This involves the evaluation of a number of complex factors. Replacement decisions will not be made on the basis of a simple comparison of one performance characteristic such as system accuracy.

The provision of Government radionavigation services is subject to the budgetary process, including authorizations and appropriations by Congress, and priorities for allocations among programs by agencies.

2.1.1 Process

The requirements for an area or class of users are not absolutes. The process to determine requirements involves:

- Evaluation of the acceptable level of safety risks to the Government, user, and general public as a function of the service provided.
- Evaluation of the economic needs in terms of service needed to provide cost-effective benefits to commerce and the public at large. This involves a detailed study of the service desired measured against the benefits obtained.
- Evaluation of the total cost impact of any government decision on radionavigation system users.

2.1.2 User Factors

User factors requiring consideration are:

- Vehicle size, speed, and maneuverability.
- Regulated and unregulated traffic flow.
- User skill and workload.
- Processing and display requirements for navigation and positioning information.
- Environmental constraints; e.g., weather, terrain, or man-made obstructions.

- Operational constraints inherent to the system.
- Safety constraints.
- Economic benefits.

For most users, cost is generally the driving consideration. The price users are willing to pay for equipment is influenced by:

- Activity of the user; e.g., recreational boaters, air taxi, general aviation, mineral exploration, helicopters, commercial shipping, and positioning, surveying, and timing.
- Vehicle performance variables such as fuel consumption, operating costs, and cargo value.
- Cost/performance trade-offs of radionavigation equipment.

Thus, in the civil sector, evaluation of a navigation system against requirements involves more than a simple comparison of accuracy and equipment performance characteristics. These evaluations must involve the operational, technical, and cost elements discussed above. Performance requirements are defined within this framework.

2.2 Civil Air Radionavigation Requirements

2.2.1 Phases of Air Navigation

The two basic phases of air navigation are en route/terminal and approach/landing.

The en route/terminal phase includes all portions of flight except that within the approach/landing phase. It contains four subphases that are categorized by differing geographic areas and operating environments as follows:

1. Oceanic En Route: This subphase covers operations over ocean areas generally characterized by low traffic density and no independent surveillance coverage.
2. Domestic En Route (High Altitude and Low Altitude Routes): Operations in this subphase are typically characterized by moderate to high traffic densities. This necessitates narrower route widths than in the oceanic en route subphase. Independent surveillance is generally available to assist in ground monitoring of aircraft position.
3. Terminal Area: Operation in the terminal area is typically characterized by moderate to high traffic densities, converging routes, and transitions in flight altitudes. Narrow route widths are required. Independent surveillance is generally available to assist in ground monitoring of aircraft position.
4. Remote Areas: Remote areas are special geographic or environmental areas characterized by low traffic density and terrain where it has been difficult to cost-effectively implement comprehensive navigation coverage. Typical of remote areas are mountainous terrain, offshore areas, and large portions of the state of Alaska.

The approach/landing phase is that portion of flight conducted immediately prior to touchdown. It is generally conducted within 20 nautical miles (nm) of the runway. Three subphases may be classified as nonprecision approach (NPA), precision approach and landing, and missed approach.

1. Nonprecision Approach: Nonprecision approach aids provide a landing aircraft with horizontal* position information (2-dimensional approaches).

2. Precision Approach and Landing: Precision approach aids provide landing aircraft with vertical and horizontal* guidance and positioning information (3-dimensional approaches).

3. Missed Approach: Missed approach procedure is conducted when a landing cannot be completed safely as determined by the pilot or Air Traffic Controller.

2.2.2 General Requirements for Aviation Navigation Systems

Aircraft navigation is the process of piloting aircraft from one place to another and includes position determination, establishment of course and distance to the desired destination, and determination of deviation from the desired track. Requirements for navigation performance are dictated by the phase of flight and their relationship to terrain, to other aircraft, and to the air traffic control process. Aircraft navigation may be achieved through the use of visual procedures during Visual Flight Rules (VFR) operations but requires navigation avionics when operating under Instrument Flight Rules (IFR) or above Flight Level (FL) 180 (18,000 ft).

Aircraft separation criteria, established by the FAA, take into account limitations of the navigation service available and, in some airspace, the Air Traffic Control (ATC) surveillance service. Aircraft separation criteria are influenced by the quality of navigation service, but are strongly affected by other factors as well. The criteria relative to separation require a high degree of confidence that an aircraft will remain within its assigned volume of airspace. The dimensions of the volume are determined, in part, by a stipulated probability that performance of the navigation system will remain within a specified error budget.

The following are basic requirements for the aviation navigation systems. “Navigation system” means all of the elements necessary to provide navigation services to each phase of flight. No single set of navigation and operational requirements, even though they meet the basic requirement for safety, can adequately address the many different combinations of operating conditions encountered in various parts of the world. Requirements applicable to the most exacting region may be considered extravagant when applied to other regions. In general, the requirements are:

a. The navigation system must be suitable for use in all aircraft types that may require the service without unduly limiting the performance characteristics or utility of those aircraft types; e.g., maneuverability, fuel economy, and combat capability.

* Horizontal accuracy is usually expressed as cross track and/or along track.

b. The navigation system must be safe, reliable, and available; and appropriate elements must be capable of providing service over all the used airspace of the world, regardless of time, weather, terrain, and propagation anomalies.

c. The integrity of the navigation system, including the presentation of information in the cockpit, shall be near 100 percent and, to the extent feasible, should provide timely alarms in the event of failure, malfunction, or interruption.

d. The navigation system must recover from a temporary loss of signal without the need for complete resetting.

e. The navigation system must provide in itself maximum practicable protection against the possibility of input blunder, incorrect setting, or misinterpretation of output data.

f. The navigation system must provide adequate means for the pilot to check the accuracy of airborne equipment.

g. The navigation information provided by the system must be free from unresolved ambiguities of operational significance.

h. Any source-referenced element of the total navigation system shall be capable of providing operationally acceptable navigation information simultaneously and instantaneously to all aircraft that require it within the area of coverage.

i. In conjunction with other flight instruments, the navigation system shall provide information to the pilot and aircraft systems for performance of the following functions:

- Continuous determination of position of aircraft.
- Continuous track deviation guidance.
- Continuous determination of distance along track.
- Position reporting.
- Manual or automatic flight.

j. The navigation system must be capable of being integrated into the overall ATC system.

k. The navigation system should provide for efficient transition through all phases of flight, for which it is designed, with minimum impact on cockpit procedure/displays and workload.

l. The navigation system must permit the pilot to determine the position of the aircraft with an accuracy and frequency that will (a) ensure that the separation minima can be maintained at all times, (b) execute properly the required holding and approach patterns, and (c) maintain the aircraft within the area allotted to the procedures.

m. The navigation system must permit the establishment and the servicing of any practical defined system of routes for the appropriate phases of flight.

n. The system must have sufficient flexibility to permit changes to be made to the system of routes and siting of holding patterns without imposing unreasonable inconvenience or cost to the providers and the users of the system.

o. The navigation system must be capable of providing the information necessary to permit maximum utilization of airports and airspace.

p. The navigation system must be cost-effective for both the Government and the users.

q. The navigation system must be designed to reduce susceptibility to interference from adjacent radio-electronic equipment and shall not cause objectionable interference to any associated or adjacent radio-electronic equipment installation in aircraft or on the ground.

r. The navigation system must compensate for signal fades or other propagation anomalies within the operating area.

s. The navigation system must be capable of furnishing reduced service to aircraft with limited equipment.

2.2.3 Navigation Signal Error Characteristics

The signal error characteristics of a navigation system have a direct effect on determining minimum route widths. The distribution and rate of change, as well as magnitude of the errors, must be considered. Error distributions may contain both bias and random components. Under certain conditions, the bias component is generally easily compensated for when its characteristics are constant and known. The magnitude, nature, and distribution of errors as a function of time, terrain, aircraft type, aircraft maneuvers, and other factors must be considered. The evaluation of errors is a complex process, and the comparison of systems based upon a single error number will be misleading or incorrect.

2.2.4 Current Aviation Navigation Accuracy Requirements for Phases of Flight

The system use accuracy requirements to meet the current route requirements for all phases of flight are summarized in Table 2-1. These route widths are based upon present capacities, separation requirements, and obstruction requirements.

Some evolving systems, such as WAAS, may have specified requirements that do not reconcile with Table 2-1. The numbers in Table 2-1 are expected to evolve to accommodate new systems. It is anticipated that the WAAS numbers will reflect the Standards and Recommended Practices (SARPs) for Global Navigation Satellite Systems (GNSS) once the SARPs are approved.

2.2.4.1 En Route/Terminal Phase

The en route/terminal phase of air navigation includes the following subphases:

- Oceanic En Route

- Domestic En Route
- Terminal Area
- Remote Area

The general requirements in Section 2.2.2 are applicable to the en route/terminal phase of flight. In addition, to facilitate aircraft navigation in this phase, the system must be capable of being operationally integrated with the system used for approach and landing.

Navigation in the vertical plane is also required for safe and efficient flight. The current separation requirement is 1,000 feet below FL 290, and 2,000 feet at and above FL 290. In order to justify the 1,000-foot vertical separation below FL 290, the RSS altitude keeping requirement is +350 feet (3 sigma). This error is comprised of +250 feet (3 sigma) aircraft altimetry system error, of which the altimeter error is limited to +125 feet by Technical Standard Order (TSO) C-10B below FL 290. Changes are being considered to reduce the vertical separation between FL 290 and FL 410 to 1,000 feet. New performance requirements will be developed.

The minimum performance criteria currently established to meet requirements for the en route/terminal phase of flight are presented in the following sections.

2.2.4.1.1 Oceanic En Route

The system must provide navigation capability commensurate with the need in specific areas in order to permit safe navigation and the application of lateral separation criteria. An organized track system has been implemented in the North Atlantic to gain the benefit of optimum meteorological conditions. Since an independent surveillance system such as radar is not available, separation is maintained by procedural means (e.g., position reports and timing).

The lateral separation standard on the North Atlantic organized track system is 60 nm. The lateral separation standard has been reduced to 50 nm in parts of the Pacific Ocean.

2.2.4.1.2 Domestic En Route

Two types of domestic air navigation are allowed under operational procedures. Fixed domestic air routes are based on the locations of VOR/DME or VORTAC facilities relative to fixed obstacles like mountains. Airspace is protected at FL 600 and below to ±4 nm on each side of the route to a point no greater than 51 nm from the navaid facility.

Area navigation is not restricted to fixed air routes. Under VFR, area navigation is allowed to be direct between the origin and destination. Under IFR, area navigation is usually restricted to FL 290 and above with separation maintained by the controller. Onboard collision avoidance with Traffic Alert and Collision Avoidance System (TCAS) is required for revenue carrier operations. VFR and IFR area navigation can be supported by GPS or Loran-C services. More commonly, air carrier operations support area navigation with flight management systems (FMS) that integrate a number of navigation sources used within the constraints of their operational service volumes to define a navigation solution. Basic RNAV performance

Table 2-1. Controlled Airspace Navigation Accuracy Requirements

PHASE	SUBPHASE		ALTITUDE FL/FT	TRAFFIC DENSITY	ROUTE WIDTH (nm)	SOURCE ACCURACY[1] CROSS –TRACK (95%, nm)	SYSTEM USE ACCURACY[2] CROSS -TRACK (95%, nm)
EN ROUTE/ TERMINAL	Oceanic		FL 275 to 400	Normal	50*	12.4*	12.6*
	Domestic		FL 180 tO 600	Low	16	2.8	3.0
				Normal	8	2.8	3.0
			500 FT to FL 180	High	8	2.8	3.0
	Terminal		500 FT to FL 180	High	4	1.7	2.0
APPROACH AND LANDING	Nonprecision		250 to 3,000 FT	Normal	N/A	0.3	0.6
	Precision	CAT I	N/A	Normal	N/A	+/-17.1 **	+/-4.1 *** CAT I Decision Height Point ****	N/A
		CAT II	N/A	Normal	N/A	+/-5.2 **	+/-1.7 *** CAT II Decision Height Point ****	N/A
		CAT III	N/A	Normal	N/A	+/-4.1 **	+/- 0.6 *** At Runway Threshold ****	N/A

1 *The requirements of the navigation sensor.*
2 *The combination of Source Accuracy and Flight Technical Error.*
* *Lateral separation requirements in the Pacific.*
** *Lateral position accuracy in meters.*
*** *Vertical position accuracy in meters.*
**** *Assumes a 3° glide slope and 8,000 ft. distance between runway threshold and localizer antenna. It may be possible to meet CAT III touchdown requirements down to the runway.*

can be sustained with scanning DME systems that interrogate the distance to multiple DME facilities and use barometric altimeter input for vertical height. VOR can be combined into this solution. ILS is added when present in a precision approach terminal. Inertial reference, airspeed, and attitude are often incorporated to stabilize the aircraft when it is flown by the FMS.

Loran-C and, more recently GPS, inputs have been added to increase area navigation accuracy.

2.2.4.1.3 Terminal Area

Terminal procedures provide transition from the en route to the approach phase of flight. Terminal VOR/DME facilities can be used to support such a procedure. Terminal surveillance facilities support controller vectoring of aircraft to intercept precision approach services in higher density terminal areas. As RNAV-equipped aircraft support more precise navigation, new terminal procedures have been developed to support these operations.

2.2.4.1.4 Remote Areas

Remote areas are defined as regions that do not meet the requirements for installation of VOR/DME service or where it is impractical to install this system. These include offshore areas, mountainous areas, and a large portion of the state of Alaska. Thus the minimum route width varies and can be greater than 10 nm.

2.2.4.1.5 Operations Between Ground Level and 5,000 Feet Above Ground Level (AGL)

Operations between ground level and 5,000 feet AGL occur in offshore, mountainous, and high-density metropolitan areas as well as on domestic routes. For operations from U.S. coastline to offshore points, the following requirements must be met:

- Range from shore to 300 nm.
- Minimum en route altitude of 500 feet above sea level or above obstructions.
- Accuracy adequate to support routes 4 nm wide or narrower with 95 percent confidence.
- Minimum descent altitude to 100 feet in designated areas.

For helicopter operations over land, the following requirements must be met:

- Accuracy adequate to support 2 nm route widths in both en route and terminal areas with 95 percent confidence.
- Minimum en route altitudes of 1,200 feet AGL.
- Navigation signal coverage adequate to support approach procedures to minimums of 250 feet above obstruction altitudes at heliports and airports.

2.2.4.2 Approach/Landing Phase

This phase of instrument flight includes two types: (1) nonprecision approach, or (2) precision approach and landing.

The general requirements of Section 2.2.2 apply to the approach/landing phase. In addition, specific procedures and clearance zone requirements are specified in TERPS (United States Standard for Terminal Instrument Procedures, FAA Handbook 8260.3B) (Ref. 4).

Altimetry accuracy requirements are established in accordance with FAR 91.411 and are the same as those for the en route/terminal phase.

The minimum performance criteria currently established to meet requirements for the approach/landing phase of navigation vary between precision and nonprecision approaches.

2.2.4.2.1 Nonprecision Approach

Nonprecision approaches are based on any navigation system that meets the criteria established in TERPS. Minimum safe altitude, obstacle clearance area, visibility minimum, final approach segment area, etc., are all functions of the navigation accuracy available and other factors. The unique features of RNAV for nonprecision approaches are specified in Reference 5.

The achieved capability for nonprecision approaches varies significantly, depending on the location of the navigation facility in relation to the fix location and type of navigation system used. Approximately 30 percent of the nonprecision approach fixes based on VOR in the U.S. achieve a cross track navigation accuracy of ±100 meters (2 sigma) at the missed approach point (MAP). This accuracy is based upon the ±4.5 degrees VOR system use accuracy and the MAP being less than 0.7 nm from the VOR facility.

Nonprecision RNAV approaches must satisfy their own criteria and are based on the obstacle clearance areas shown in Figure 2-1. The width of the intermediate approach trapezoid primary areas decreases from 4 nm (2 nm each side of the route centerline) at the end of the intermediate fix or waypoint displacement area to 2 nm (1 nm each side of the route centerline) at the final approach fix or waypoint. Primary obstacle clearance areas further narrow to the width of the runway waypoint fix displacement area at its furthest point. Secondary areas (not depicted) also extend upward and outward from the sides of the primary area.

The integrity time-to-alarm requirement for nonprecision approaches provides the pilot with either a warning or a removal of signal within 10 seconds of the occurrence of an out-of-tolerance condition.

2.2.4.2.2 Precision Approach and Landing

A precision approach and landing aid provides a landing aircraft with vertical and horizontal guidance and position information. The current worldwide standard systems for precision approach and landing are the Instrument Landing System (ILS) and the Microwave Landing System (MLS). International agreements have been made to achieve an all-weather landing capability through an evolutionary process, reducing landing weather minima on a step-by-step basis as technical capabilities and operational knowledge permit. The accuracy requirements for the various landing categories are shown in Table 2-1. A range of values is provided for Category I precision approach. The 95 percent accuracy requirement depends upon the error characteristics of the system, such as the frequency and correlation of errors. ILS has an angular error characteristic and has both low-frequency and high-frequency components. The 95 percent accuracy for ILS at a 200-foot decision height is 4.1 meters. The Category II/III accuracy of 2 meters is equal to the accuracy of ILS at 100 feet above the runway. Aircraft use a combination of the landing system and a radar altimeter to accomplish a Category III approach.

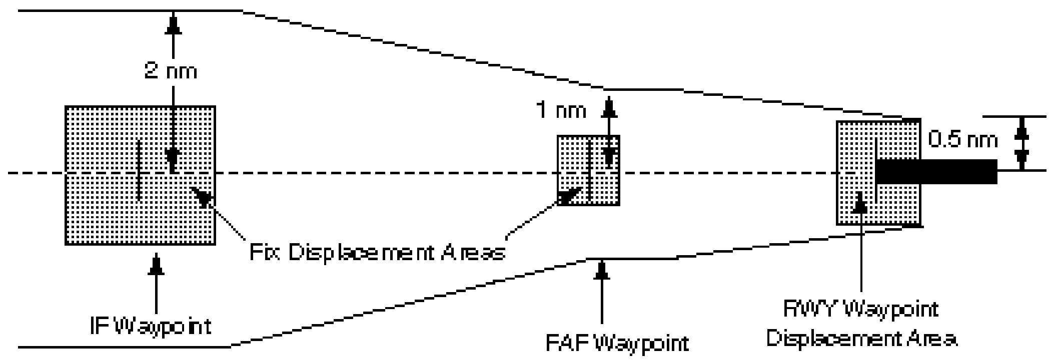

Figure 2-1. RNAV Nonprecision Approach Protected Areas

Precision approach and landing systems are required to warn the pilot of an out-of-tolerance condition during precision approaches by removing these signals from service. The response time for providing these warnings varies from six seconds for Category I to two seconds for Category II/III.

2.2.5 Future Aviation Navigation Requirements

Aviation navigation requirements are evolving toward the concept of Required Navigation Performance (RNP). The RNP concept establishes criteria for airworthiness approval, ground equipment approval (if required), operating approval, establishment of operating minima and obstacle clearance assessment.

Altimetry requirements for vertical separation of 1,000 feet, below FL 290, are not expected to change. Increased altimetry accuracy is needed at and above FL 290 to permit separation less than the current standard of 2,000 feet. The required future 3 sigma value of the aircraft altimetry system error has not been specified, but it must be accurate enough to support the introduction of 1,000-foot vertical separation at all flight levels.

2.2.5.1 En Route/Terminal Phase

2.2.5.1.1 Oceanic En Route

Current separation specifications have been designed to allow a lateral separation of 60 nm. This was put into effect for certain areas of the North Atlantic in early 1981 and requires a lateral track error less than ±12.6 nm (95 percent). More accurate and reliable aircraft position data will greatly contribute to reductions in lateral separation, resulting in greater flexibility and the ability to fly user-preferred routes. Some route separations in the Pacific area have been reduced to 50 nm.

2.2.5.1.2 Domestic En Route

At the present time, the number of VOR/DMEs is sufficient to allow most routes to have widths of ±4 nm. This is possible as most VOR facilities are spaced less than 100 nm apart on the route. However, greater spacings are used in low traffic density areas, remote areas, and on most of the high-altitude route structure. Parts of the high-altitude route structure have a distance between VOR facilities resulting in route widths up to 20 nm.

Traffic increases may soon exceed capacity. More use of RNAV will allow the implementation of random and parallel routes not possible with the use of current VOR/DME facilities, thus easing the capacity problem. No increase in VOR/DME ground accuracy is required to meet the navigation requirements imposed by the air traffic levels estimated for the year 2000.

2.2.5.1.3 Terminal Area

The major change forecasted for the terminal area is the increased use of RNAV and time control to achieve optimum runway utilization and noise abatement procedures. Some current multi-DME RNAV avionics can provide cross track navigation accuracies better than ±500 meters (2 sigma) in terminal areas using the current VOR/DME facilities. Similarly, GPS-based avionics deliver better accuracies and performance than VOR/DME.

2.2.5.1.4 Remote Areas

Many areas, such as Alaska, the Rocky Mountains and other mountainous areas, and some offshore locations, cannot be served easily or at all by VOR/DME. Presently, nondirectional beacons (NDB), and privately owned facilities such as TACAN are being used in combination to meet the user navigation needs in these areas. GPS and Loran-C are being used as supplements to VOR/DME to meet these needs. The accuracy and coverage of these systems seem adequate to handle the traffic densities projected for the different areas.

2.2.5.2 Approach/Landing Phase

2.2.5.2.1 Nonprecision Approach

Nonprecision approach obstacle clearance areas may be reduced to take advantage of the increased performance by augmented GPS.

2.2.5.2.2 Precision Approach and Landing

Future requirements for precision approaches will be developed for specific systems using the RNP concept. The RNP concept provides a framework to drive requirements based on the need to avoid obstacles and place the aircraft in a position to land.

2.3 Civil Marine Radionavigation Requirements

2.3.1 Phases of Marine Navigation

Marine navigation in the U.S. consists of four major phases identified as inland waterway, harbor entrance and approach, coastal, and ocean navigation. Standards or requirements for safety of navigation and reasonable economic efficiency can be developed around these four phases. Specialized requirements, which may be generated by the specific activity of a ship, must be addressed separately.

2.3.1.1 Inland Waterway

Inland waterway navigation is conducted in restricted areas similar to those for harbor entrance and approach. However, in the inland waterway case, the focus is on non-seagoing ships and their requirements on long voyages in restricted waterways, typified by tows and barges in the U.S. Western Rivers System and the U.S. Intracoastal Waterway System.

In some areas, seagoing craft in the harbor phase of navigation and inland craft in the inland waterway phase share the use of the same restricted waterway. The distinction between the two phases depends primarily on the type of craft. It is made because seagoing ships and typical craft used in inland commerce have differences in physical characteristics, personnel, and equipment. These differences have a significant impact upon their requirements for aids to navigation. Recreational and other relatively small craft are found in large numbers in waters used by both seagoing and inland commercial traffic and generally have less rigid requirements in either case.

2.3.1.2 Harbor Entrance and Approach

Harbor entrance and approach navigation is conducted in waters inland from those of the coastal phase. For a ship entering from the sea or the open waters of the Great Lakes, the harbor approach phase begins generally with a transition zone between the relatively unrestricted waters where the navigation requirements of coastal navigation apply, and narrowly restricted waters near and/or within the entrance to a bay, river, or harbor, where the navigator enters the harbor phase of navigation. Usually, harbor entrance requires navigation of a well-defined channel which, at the seaward end, is typically from 180 to 600 meters in width if it is used by large ships, but may narrow to as little as 120 meters farther inland. Channels used by smaller craft may be as narrow as 30 meters.

From the viewpoint of establishing standards or requirements for safety of navigation and promotion of economic efficiency, there is some generic commonality in harbor entrance and approach. In each case, the nature of the waterway, the physical characteristics of the vessel, the need for frequent maneuvering of the vessel to avoid collision, and the closer proximity to grounding danger impose more stringent requirements for accuracy and for real-time guidance information than for the coastal phase.

For analytical purposes, the phase of harbor entrance and approach is built around the problems of precise navigation of large seagoing and Great Lakes ships in narrow channels between the transition zone and the intended mooring.

2.3.1.3 Coastal Navigation

Coastal navigation is that phase in which a ship is within 50 nm from shore or the limit of the continental shelf (200 meters in depth), whichever is greater, where a safe path of water at least one mile wide, if a one-way path, or two miles wide, if a two-way path, is available. In this phase, a ship is in waters contiguous to major land masses or island groups where transoceanic traffic patterns tend to converge in approaching destination areas; where interport traffic exists in patterns that are essentially parallel to coastlines; and within which ships of lesser range usually confine their operations. Traffic-routing systems and scientific or industrial activity on the continental shelf are encountered frequently in this phase of navigation. Ships on the open waters of the Great Lakes also are considered to be in the coastal phase of navigation.

The boundary between coastal and ocean navigation is defined by one of the following which is farthest from land:

- 50 nm from land.
- The outer limit of offshore shoals, or other hazards on the continental shelf.
- Other waters where traffic separation schemes have been established, and where requirements for the accuracy of navigation are thereby made more rigid than the safety requirements for ocean navigation.

2.3.1.4 Ocean Navigation

Ocean navigation is that phase in which a ship is beyond the continental shelf (200 meters in depth), and more than 50 nm from land, in waters where position fixing by visual reference to land or to fixed or floating aids to navigation is not practical. Ocean navigation is sufficiently far from land masses so that the hazards of shallow water and of collision are comparatively small.

2.3.2 Current Marine Navigation Requirements

The navigation requirements of a vessel depend upon its general type and size, the activity in which the ship is engaged (e.g., point-to-point transit, fishing) and the geographic region in which it operates (e.g., ocean, coastal), as well as other factors. Safety requirements for navigation performance are dictated by the physical constraints imposed by the environment and the vessel, and the need to avoid the hazards of collision, ramming, and grounding.

The above discussion of phases of marine navigation sets the framework for defining safety of navigation requirements. However, the economic and operational dimensions also need to be considered for the wide diversity of vessels that traverse the oceans and U.S. waters. For example, navigation accuracy (beyond that needed for safety) is particularly important to the economy of large seagoing ships having high hourly operating costs. For fishing and oil exploration vessels, the ability to locate precisely and return to productive or promising areas and at the same time avoid underwater obstructions or restricted areas provides important economic benefits. Search and Rescue (SAR) effectiveness is similarly dependent on accurate navigation in the vicinity of a maritime distress incident.

For system planning, the Government seeks to satisfy minimum safety requirements for each phase of navigation and to maximize the economic utility of the service for users. Since the vast majority of marine users are required to carry only minimal navigation equipment, and even then do so only if persuaded by individual cost/benefit analysis, this governmental policy helps to promote maritime safety through a simultaneous economic incentive.

Tables 2-2, 2-3, 2-4, and 2-5 identify system performance needed to satisfy maritime user requirements or to achieve special benefits. The requirements are related to safety of navigation. The Government recognizes an obligation to satisfy these requirements for the overall national interest. The benefits are specialized requirements or characteristics needed to provide special benefits to discrete classes of maritime users (and additional public benefits which may accrue from services provided by users). The Government does not recognize an absolute commitment to satisfy these requirements, but does endeavor to meet them if their cost can be justified by benefits that are in the national interest. For the purpose of comparing the performance of systems, the requirements are categorized in terms of system performance characteristics representing the minimum performance considered necessary to satisfy the requirements or achieve special benefits.

2.3.2.1 Inland Waterway Phase

Very large amounts of commerce move on the U.S. inland waterway system, much of it in slow-moving, comparatively low-powered tug and barge combinations. Tows on the inland waterways, although comparatively shallow in draft, may be longer and wider than large seagoing ships that call at U.S. ports. Navigable channels used by this inland traffic are often narrower than the harbor access channels used by large ships. Restricted visibility and ice cover present problems in inland waterway navigation, as they do in harbor entrance and approach navigation. The long, ribbon-like nature of the typical inland waterway presents special problems to the prospective user of precise, land-based area navigation systems. Continual shifting of navigable channels in some unstable waters creates additional problems to the prospective user of any radionavigation system that provides position measurements in a fixed coordinate system.

Special waterways, such as the Saint Lawrence River and some Great Lakes passages, are well defined, but subject to frequent fog cover which requires ships to anchor. This imposes a severe economic penalty in addition to the safety issues. If a fog rolls in unexpectedly, a ship may need to proceed under hazardous conditions to an anchorage clear of the channel or risk stopping in a channel. Current requirements for the inland waterway phase of navigation are provided in Table 2-2.

Table 2-2. Current Maritime User Requirements for Purposes of System Planning and Development - Inland Waterway Phase

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS								
	ACCURACY (meters, 2drms)		COVERAGE	AVAILABILITY	RELIABILITY	FIX INTERVAL (seconds)	FIX DIMENSIONS	SYSTEM CAPACITY	AMBIGUITY
	PREDICTABLE	REPEATABLE							
Safety of Navigation (All Ships & Tows)	2-5	2-5	US Inland Waterway Systems	99.9%	*	1-2	2	Unlimited	Resolvable with 99.9% confidence
Safety of Navigation (Recreational Boats & Smaller Vessels)	5-10	5-10	US Inland Waterway Systems	99.9%	*	5-10	2	Unlimited	Resolvable with 99.9% confidence
River Engineering & Construction Vessels	0.1**-5	0.1**-5	US Inland Waterway Systems	99%	*	1-2	2 or 3	Unlimited	Resolvable with 99.9% confidence

* Dependent upon mission time.

** Vertical dimension.

Table 2-3. Current Maritime User Requirements/Benefits for Purposes of System Planning and Development - Harbor Entrance and Approach Phase

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS								
	ACCURACY (meters, 2drms)		COVERAGE	AVAILABILITY	RELIABILITY	FIX INTERVAL (seconds)	FIX DIMENSIONS	SYSTEM CAPACITY	AMBIGUITY
	PREDICTABLE	REPEATABLE							
Safety of Navigation (Large Ships & Tows)	8-20***	-	US harbor entrance and approach	99.7%	**	6-10	2	Unlimited	Resolvable with 99.9% confidence
Safety of Navigation (Smaller Ships)	8-20	8-20	US harbor entrance and approach	99.9%	**	***	2	Unlimited	Resolvable with 99.9% confidence
Resource Exploration	1-5*	1-5*	US harbor entrance and approach	99%	**	1	2	Unlimited	Resolvable with 99.9% confidence
Engineering & Construction Vessels Harbor Phase	0.1****-5	0.1****-5	Entrance channel & jetties, etc.	99%	**	1-2	2 and 3	Unlimited	Resolvable with 99.9% confidence
Benefits	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS								
Fishing, Recreational & Other Small Vessels	8-20	4-10	US harbor Entrance and approach	99.7%	**	***	2	Unlimited	Resolvable with 99.9% confidence

* Based on stated user need.

** Dependent upon mission time.

*** Varies from one harbor to another. Specific requirements are being reviewed by the Coast Guard.

**** Vertical dimension.

Table 2-4. Current Maritime User Requirements/Benefits for Purposes of System Planning and Development - Coastal Phase

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS								
	ACCURACY (meters, 2drms)		COVERAGE	AVAILABILITY	RELIABILITY	FIX INTERVAL	FIX DIMENSIONS	SYSTEM CAPACITY	AMBIGUITY
	PREDICTABLE	REPEATABLE							
Safety of Navigation (All Ships)	0.25nm (460m)	-	US coastal waters	99.7%	**	2 minutes	2	Unlimited	Resolvable with 99.9% confidence
Safety of Navigation (Recreation Boats & Other Smaller Vessels)	0.25nm-2nm (460-3,700m)	-	US coastal waters	99%	**	5 minutes	2	Unlimited	Resolvable with 99.9% confidence

BENEFITS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS								
Commercial Fishing (Including Commercial Sport Fishing)	0.25nm (460m)	50-600 ft (15-180m)	US coastal/ Fisheries areas	99%	**	1 minute	2	Unlimited	
Resource Exploration	1.0-100m*	1.0-100m*	US coastal areas	99%	**	1 second	2	Unlimited	
Search Operations, Law Enforcement	0.25nm (460m)	300-600 ft (90-180m)	US coastal/ Fisheries areas	99.7%	**	1 minute	2	Unlimited	
Recreational Sports Fishing	0.25nm (460m)	100-600 ft (30-180m)	US coastal areas	99%	**	5 minutes	2	Unlimited	Resolvable with 99.9% confidence

* Based on stated user need.
** Dependent upon mission time.

Table 2-5. Current Maritime User Requirements/Benefits for Purposes of System Planning and Development - Ocean Phase

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS									
	ACCURACY (2 drms)			COVERAGE	AVAILABILITY	RELIABILITY	FIX INTERVAL	FIX DIMENSION	SYSTEM CAPACITY	AMBIGUITY
	PREDICTABLE	REPEATABLE	RELATIVE							
Safety of Navigation (All Craft)	2-4nm (3.7-7.4km) minimum 1-2nm (1.8-3.7km) desirable	-	-	Worldwide	99% fix at least every 12 hours	**	15 minutes or less desired; 2 hours maximum	2	Unlimited	Resolvable with 99.9% confidence

BENEFITS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS									
Large Ships Maximum Efficiency	0.1-0.25nm* (185-460m)	-	-	Worldwide, except polar regions	99%	**	5 minutes	2	Unlimited	Resolvable with 99.9% confidence
Resource Exploration	10-100m*	10-100m*	-	Worldwide	99%	**	1 minute	2	Unlimited	Resolvable with 99.9% confidence
Search Operations	0.1-0.25nm (185-460m)	0.25nm	0.1nm (185m)	National Maritime SAR regions	99%	**	1 minute	2	Unlimited	Resolvable with 99.9% confidence

* Based on stated user need.

** Dependent upon mission time.

2.3.2.2 Harbor Entrance and Approach Phase

The pilot of a vessel in restricted waters must direct its movement with great accuracy and precision to avoid grounding in shallow water, hitting submerged/partially submerged rocks, and colliding with other craft in congested waterways. Unable to turn around, and severely limited in the ability to stop to resolve a navigation problem, the pilot of a large vessel (or a tow boat and barge combination) may find it necessary to hold the total error in navigation within limits measured in a few feet while navigating in this environment.

To navigate safely, the pilot needs highly accurate verification of position almost continuously, together with information depicting any tendency for the vessel to deviate from its intended track and a nearly continuous and instantaneous indication of the direction in which the pilot should steer. Table 2-3 was developed to present estimates of these requirements. To effectively utilize the requirements stated in the table, however, a user must be able to relate the data to immediate positioning needs. This is not practical if one attempts to plot fixes on a chart in the traditional way. To utilize radionavigation information that is presented at less than 10-second intervals on a moving vessel, some form of an automatic display is required. Technology is available which presents radionavigation information along with other data.

Minimum Performance Criteria: The radionavigation system accuracy required to provide useful information in the harbor entrance and approach phase of marine navigation varies from harbor to harbor, as well as with the size of the vessel. In the more restricted channels, accuracy in the range of 8 to 20 meters (2 drms) may be required for the largest vessels. A need exists to more accurately determine these radionavigation requirements for various-sized vessels while operating in such restricted confines. Radionavigation user conferences have indicated that for many mariners, the radionavigation system becomes a secondary tool when entering the harbor entrance and approach environment.

Continuing efforts are being directed toward verifying user requirements and desires for radionavigation systems in the harbor entrance and approach environment.

2.3.2.3 Coastal Phase

There is a need for continuous, all-weather radionavigation service in the coastal area to provide, at the least, the position fixing accuracy to satisfy minimum safety requirements for general navigation. These requirements are delineated in Table 2-4. Furthermore, the total navigation service in the coastal area must provide service of useful quality and be within the economic reach of all classes of mariners.

Requirements on the accuracy of position fixing for safety purposes in the coastal phase are established by:

- The need for larger vessels to navigate within the designated one-way traffic lanes at the approaches to many major ports, in fairways established through offshore oil fields, and at safe distances from shallow water.

- The need to define accurately, for purposes of observing and enforcing U.S. laws and international agreements, the boundaries of the Fishery Conservation Zone, the U.S. Customs Zone, and the territorial waters of the U.S.

Minimum Performance Criteria: Government studies have established that a navigation system providing a capability to fix position to an accuracy of 0.25 nm will satisfy the minimum safety requirements if a fix can be obtained at least every 15 minutes. As a secondary economic factor, it is required that relatively higher repeatable accuracy be recognized as a major advantage in the consideration of alternative candidate radionavigation systems for the coastal area. As indicated in Table 2-4, these requirements may be relaxed slightly for the recreational boaters and other small vessels.

In such activities as marine scientific research, hydrographic surveying, commercial fishing, and petroleum or mineral exploration, as well as in Navy operations, there may be a need to establish position in the coastal area with much higher accuracy than that needed for safety of general navigation. In many of these special operations that require highly accurate positions, the use of radiodetermination would be classified as radiolocation rather than radionavigation. As shown in Table 2-4, the most rigid requirement of any of this general group of special operations is for seismic surveying with a repeatable accuracy on the order of 1 to 100 meters (2 drms), and a fix rate of once per second for most applications.

2.3.2.4 Ocean Phase

The requirements for safety of navigation in the ocean phase for all ships are given in Table 2-5. These requirements must provide the Master with a capability to avoid hazards in the ocean (e.g., small islands, reefs) and to plan correctly the approach to land or restricted waters. For many operational purposes, repeatability is necessary to locate and return safely to the vicinity of a maritime distress, as well as for special activities such as hydrography, research, etc. Economic efficiency in safe transit of open ocean areas depends upon the continuous availability of accurate position fixes to enable the vessel to follow the shortest safe route with precision, minimizing transit time.

For safe general navigation under normal circumstances, the requirements for the accuracy and frequency of position fixing on the high seas are not very strict. As a minimum, these requirements include a predictable accuracy of 2 to 4 nm coupled with a maximum fix interval of 2 hours or less. These minimum requirements would permit reasonably safe oceanic navigation, provided that the navigator understands and makes allowances for the probable error in navigation, and provided that more accurate navigation service is available as land is approached. While these minimum requirements would permit all vessels to navigate with relative safety on the high seas, more desirable requirements would be predictable accuracy of 1 to 2 nm and a fix interval of 15 minutes or less. The navigation signal should be available 95 percent of the time. Further, in any 12-hour period, the probability of obtaining a fix from the system should be at least 99 percent.

Larger recreational craft and smaller commercial fishing vessels which sail beyond the range of coastal navigation systems require, for a reasonable level of safety, some means of establishing their position reliably at intervals of a few hours at most. Even more so than with larger ships, this capability is particularly important in time of emergency or distress. Many operators of these craft, however, will accept the risk of ocean sailing without reliable radionavigation unless that capability is available at relatively low cost.

Minimum Performance Criteria: Economic efficiency in transoceanic transportation, special maritime activities and safety in emergency situations require or benefit from navigation accuracy higher than that needed for safety in routine, point-to-point ocean voyages. These requirements are summarized in Table 2-5. The predictable accuracy benefits may be as stringent as 10 meters for special maritime activities, and may range to 0.25 nm for large, economically efficient vessels, including search operations. Search operations must also have a repeatable accuracy of at least 0.25 nm. As indicated in Table 2-5, the required fix interval may range from as low as once per 5 minutes to as high as once per minute. Signal availability must be at least 95 percent and approach 99 percent for all users.

2.3.3 Future Marine Navigation Requirements

The marine radionavigation requirements presented in the preceding discussions and tables are based on a combination of requirements studies, user inputs, and estimates. However, they are the product of current technology and operating practices, and are therefore subject to revision as technologies and operating techniques evolve. The principal factors that will impact future requirements are safety, economics, environment, and energy conservation.

Special radionavigation requirements may arise from new environmental laws and regulations designed to reduce marine vessel casualty events. Also, the role of commercial ships in military sealift missions may require additional navigation systems capabilities.

2.3.3.1 Safety

2.3.3.1.1 Increased Risk from Collision and Grounding

Hazardous cargoes (petroleum, chemicals, etc.) are carried in great volumes in U.S. coastal and inland waterways. Additionally, the ever increasing volume of other shipping, the ability to operate at increased speed, and the increasing numbers of smaller vessels act to constantly increase the risk of collision and grounding. Economic constraints also cause vessels to be operated in a manner which, although not unsafe, places more stringent demands on all navigation systems.

2.3.3.1.2 Increased Size and Decreased Maneuverability of Marine Vessels

The desire to minimize costs and to capture economies of scale in marine transportation have led to design and construction of larger vessels and unitized tug/barge combinations, both of which are relatively less powerful and maneuverable than their predecessors. Consequently, improved navigation performance is needed.

2.3.3.1.3 Greater Need for Traffic Management/Navigation Surveillance Integration

The foregoing trends underlie the importance of continued governmental involvement in marine vessel traffic management to assure reasonable safety in U.S. waters. Radionavigation systems may become an essential component of traffic management systems. Differential GPS and Automated Identification Systems (AIS) are expected to play an increasingly important role in areas such as Vessel Traffic Services (VTS).

2.3.3.2 Economics

2.3.3.2.1 Greater Congestion in Inland Waterways and Harbor Entrances and Approaches

In addition to the safety penalty implicit in greater congestion in restricted waterways, there are economic disadvantages if shore facilities are not used effectively and efficiently. Accurate radionavigation systems can contribute to better productivity and decreased delay in transit.

2.3.3.2.2 All Weather Operations

Low visibility and ice-covered waters presently impact maritime operations. Future radionavigation systems may eventually alleviate the impact of these restrictions.

2.3.3.3 Environment

As onshore energy supplies are depleted, resource exploration and exploitation will move farther offshore toward the U.S. outer continental shelf and to harsher and more technically demanding environments. In addition, fishing is expected to continue in the U.S. Exclusive Economic Zone. In summary, both sets of activities may generate demands for navigation services of higher quality and for broadened geographic coverage in order to allow environmentally sound development of resources.

2.3.3.4 Energy Conservation

The need to conserve energy resources and to reduce costs provides powerful incentives for increased transportation efficiency, some of which could come from better navigation systems.

2.4 Space Radionavigation Requirements

2.4.1 Space User Community

NASA is currently using GPS to support earth orbiting satellites conducting space and earth science missions and plans to extend the use of GPS in the future to human space exploration missions as well. In addition, other government agencies may use GPS on satellites in the future. There are also numerous examples of GPS use by the U.S. commercial space community for Low Earth Orbiting (LEO) communication satellite constellations and aboard commercial earth sensing satellites.

2.4.2 Space User Community Application of GPS

The U.S. space community uses GPS in a number of spacecraft and science instrument applications. Onboard satellites, GPS is being used to determine satellite position as an input to navigation software that calculates and propagates the satellite's orbit. GPS also can provide accurate time synchronization for satellites as well as spacecraft attitude determination.

NASA is also experimenting with the use of dual frequency GPS receivers aboard science satellites to conduct atmospheric occultation experiments. In this application, the GPS receiver actually becomes an instrument for measuring atmospheric temperature and moisture content. The NPOESS is currently planning to use GPS atmospheric occultation for routine atmospheric measurements aboard its satellites beginning in the next decade.

The U.S. space community also plans to use GPS for various launch vehicle applications in the future. DOD is currently planning to convert the national spacelift ranges to use GPS for range safety. This is an important aspect of DOD's Range Standardization and Automation (RSA) program. In addition, NASA is planning to use GPS for launch vehicle navigation and control functions on the Reusable Launch Vehicle (RLV) now under development. The RLV will use GPS in all three phases of its flight: launch; orbital operations; re-entry and landing. NASA will also begin using GPS for the re-entry and landing phases for the Space Shuttle in 1999.

2.4.3 Current Space Radionavigation Requirements

The use of GPS for space applications falls into three different categories:

1. Onboard spacecraft vehicle navigation support where GPS and GPS augmentations will be used in near real-time applications for navigation, precise time, and attitude determination. In this role, onboard navigation and attitude accuracy requirements are:

    - Three-dimensional position error not to exceed 1 m (1 sigma).
    - Three-dimensional velocity error not to exceed 0.1 m/sec (1 sigma).
    - Attitude determination error not to exceed 0.1 degree in each axis (1 sigma).

- Clock offset error between coordinated universal time (UTC) as maintained at the U.S. Naval Observatory (USNO) and the GPS time scale not to exceed 1 microsecond (1 sigma).

It should be noted that the required accuracies above result from filtered GPS data and do not represent instantaneous solution requirements.

2. Scientific data analysis support where GPS will be used in a post-processing mode to accurately locate instrument position in space when measurements are taken. Current accuracy requirements are to determine position within 5 cm. However, more accurate positioning in the 1 to 2 cm range may be required in the future for some earth observation instruments.
3. Use of GPS receivers aboard satellites as scientific instruments for atmospheric research. These receivers require dual frequency GPS signals in order to measure the occultation of the GPS signals as they pass through the atmosphere. This application has been demonstrated in the GPSMET experiment and is the basis behind planned instruments for the future NPOESS.

Planned and proposed future NASA spacecraft will require continued use of GPS. Examples of GPS space applications include the following:

- The Space Shuttle will implement GPS for re-entry and landing phases beginning in 2000, and will evolve to on-orbit operations in the near future. Space Shuttle experiments in the use of GPS in the ascent phase of flight will also continue.

- The International Space Station (ISS) will use GPS for position and navigation, attitude determination, and as a precise time source. Present planning is for the ISS GPS system to become active on ISS assembly flight 8A.

- Crew Return Vehicle (CRV) is the emergency return vehicle that would be used in the event of a crew emergency aboard the ISS and it will depend upon GPS for critical navigation and attitude determination functions. It will use GPS to initially align its avionics systems after separation from the ISS, use GPS for orbit phase navigation and attitude determination, for navigation during descent, and for navigation to its recovery area.

- New small satellite programs to explore low-cost access to space will implement GPS for navigation, time, and attitude determination functions. The use of low cost onboard GPS receivers for these basic functions of space flight will become a significant factor in providing inexpensive access to space for future NASA and commercial small satellite projects.

- Where scientific data position accuracy is required with precision greater than that readily available from the GPS receiver onboard a spacecraft, post-pass processing of orbit data will be used. NASA has developed post pass-process techniques using GPS on the TOPEX/POSEIDON satellite that routinely provides satellite positioning accuracy at the 5 cm level. However, in order to obtain this level of precise, accurate GPS satellite position data must be obtained. This accurate GPS satellite tracking data is developed using an extensive global network of ground monitoring stations.

- The use of GPS out to geosynchronous orbit altitudes is being explored by NASA and may prove to be useful to the commercial space industry in the future. However, it is essential that future GPS satellite power levels and beam coverage patterns remain consistent with the current signal characteristics in order to meet the needs of future space users in the geosynchronous orbital region.

- Both of NASA's RLV development efforts, the X-33 and X-34, will depend upon GPS for navigation data throughout their flight regime. This includes the use of GPS during the launch, orbit, and re-entry and landing phases. Initial flights of these vehicles will occur in 1999 - 2000 time frame.

2.5 Civil Land Radionavigation Requirements

In comparison with the air and marine communities, phases of land navigation are not well defined. Radionavigation requirements are more easily categorized in terms of applications. The land navigation applications fall into three basic categories; highway, transit, and rail applications. Ongoing work on Intelligent Transportation Systems (ITS), which includes research and development (R&D) and operational test programs funded by the Department of Transportation's modal administrations (including FHWA, FTA, FRA, and NHTSA) as well as by State and local governments and private industry, will aid in clarifying and validating user requirements.

2.5.1 Categories of Land Transportation

2.5.1.1 Highways

Radionavigation techniques in highway applications are used autonomously or are integrated with vehicle-to-roadside communications and map-matching techniques to provide various user services. These are public sector operational tests ongoing for integrated ITS systems, where radionavigation is a part of the system. However, a number of consumer products and products for use by the public sector are on the market today. Deployment of these systems is accelerating at a rapid pace. Vehicle location systems for emergency service, providers of mayday services, route navigation for private automobiles, and tracking and scheduling of commercial vehicles are in use. Examples of systems in development include augmentation of GPS vehicle location data by providing DGPS correction values over wireless communications. Also under development is a system for vehicle location monitoring using GPS integrated with wireless packet data systems. Examples of systems used in operational tests for ITS funded by FHWA include the use of radionavigation for automatic vehicle location for mayday response, route guidance, mass transit scheduling, and mileage determination. Examples of systems that are fielded and operational include radionavigation for dispatching roadside assistance vehicles and automated location tracking and scheduling of commercial vehicles. In addition to these examples, radionavigation is used by various highway departments for asset management by using GPS coordinates to identify locations of bridges, highway signs, and overpasses. Table 2-6 shows examples of ITS user services requiring the use of radionavigation. A complete description of all of the ITS user services can be found in ITS Architecture documentation (Ref. 6).

2.5.1.2 Transit

Transit systems also benefit from the same radionavigation-based technologies. Automatic vehicle location techniques assist in fleet management, scheduling, real-time customer information, and emergency assistance. In addition, random route transit

Table 2-6. ITS User Services Requiring Use of Radionavigation

Travel and Transportation Management Pre-Trip Travel Information En Route Driver Information Route Guidance Incident Management Travel Demand Management
Public Transportation Operations Public Transportation Management Personalized Public Transportation
Commercial Vehicle Operations Commercial Fleet Management
Emergency Management Emergency Vehicle Management Emergency Notification and Personal Security
Advanced Vehicle Control and Safety Systems Intersection Collision Avoidance

operations will benefit from route guidance in rural and low density areas. Also, services such as automated transit stop annunciation are being implemented. Benefits of radiolocation for public transit, when implemented with a two-way communications system, have been proven in a number of deployments across the U.S. Improvements in on-time performance, efficiency of fleet utilization, and response to emergencies have all been documented. Currently, there are over 10,000 buses in cities that employ automatic vehicle location using GPS for these fleet management functions and the deployment is spreading rapidly.

2.5.1.3 *Rail*

Nationwide DGPS can significantly aid the development of positive train control (PTC) systems by providing an affordable and reliable location determination system that is available to surface and marine transportation throughout the contiguous United States and Alaska.

New PTC systems will be communication-based; they will depend upon use of data communication over a variety of paths, including radio, to gather information for integration by microprocessors. One of the principal issues related to PTC is affordability. If systems are highly affordable, they will be widely deployed for both safety and business purposes. Wide deployment will mean that collision avoidance and other safety features will be available over a larger portion of the national rail system. Universal equipping of trains with on-board systems will be necessary to realize maximum safety benefits.

Railroads and their suppliers have evaluated their requirements for train location in relation to NDGPS as follows:

- The single most stressing requirement for the location determination system to support the PTC system is the ability to determine which of two tracks a given train is occupying with a very high degree of assurance* (an assurance that must be greater than 0.99999 or (0.9_5)). The minimum center-to-center spacing of parallel tracks is 11.5 feet. Direct GPS *will not* satisfy this requirement.
- Train location is a *one*-dimensional issue, with well-defined discrete points (switches) where the potential for diverging paths exists. NDGPS narrows the location to less than 5 meters (16 feet). The most frequent interval at which successive turnouts can be located (locations at which a train may diverge from its current route over a switch) is 48 feet. Since the train is constrained to be *located on a track*, as opposed to somewhere within an area, this collapses the problem from a two- or three-dimensional problem into a *one*-dimensional problem.
- The *detailed* track geometry data for a specific route are stored on-board the locomotive (needed for calculating the safe braking distance algorithm). Which of two parallel tracks a train is occupying can then be determined by maintaining a continuous record of which direction the train took over each diverging switch point (normal or reversed). There are several heading reference system techniques available to make this determination.

Private sector freight railroads and public sector passenger and commuter railroads own and maintain their rights-of-way, and many are using GPS for surveying to establish more accurate track maps and property inventories.

* The assurance of a navigation system is the probability over both time and area, that the services will be sufficiently robust to meet the requirements of the user. This differs from availability in that it goes beyond time and beyond a single navigation system. An example is the system envisioned for PTC. This system, as currently envisoned, will use NDGPS, inertial sensors, transponders at critical junctions, map matching, and other techniques to form an integrated navigation solution.

2.5.2 *Current Land Transportation Requirements*

For the functions of collision avoidance and automated highway operation, there has been a trend to make these functions self contained as opposed to using radionavigation services. However, because these technologies are still in the research stage, dependence on radionavigation remains a possibility with its attendant stringent accuracy requirements.

Requirements for use of radionavigation systems for land vehicle applications continue to evolve. Many civil land applications that use radionavigation systems are now commercially available. Examples of highway user applications that are now available include in-vehicle navigation and route guidance, automatic vehicle location, automated vehicle monitoring, automated dispatch, and hazardous materials tracking. Other applications continue to be investigated and developed, including resource management, highway inventory control, and positive train separation. At the present time, there are many hundreds of thousands of GPS receivers in use for surface applications. Many of these are finding their way into land vehicle applications.

In order for some of the envisioned applications to be useful, they need to be coupled with a variety of space and terrestrial communication services that relay information from the vehicle to central dispatch facilities, emergency service providers, or other destinations. An example of such an application includes relaying the status of vehicle onboard systems and fuel consumption to determine allocation of fuel taxes.

ITS operational tests are yielding results that make it clear that large scale deployment will include a number of navigation mechanisms shared with other systems and services. For example, several ITS operational tests use GPS, which is already being shared with numerous other systems and communities, along with radiobeacon systems and other radiolocation systems. Such an approach for sharing brings benefits of more efficient use of the scarce radio frequency spectrum as well as reduction of capital cost of infrastructure and related operations, administration and maintenance costs.

The navigation accuracy, availability, and integrity needs and requirements of land modes of transportation, as well as their associated security needs and requirements (including continuity of service), have been documented in the December 1994 *A Technical Report to the Secretary of Transportation on a National Approach to Augmented GPS Services* and the December 1993 *Report of the Joint DOD/DOT Task Force - The Global Positioning System: Management and Operation of a Dual Use System* (Ref. 7, 8). Examples of land transportation positioning and navigation system accuracy needs and requirements are shown in Table 2-7.

Of special interest is the concept of collision avoidance. There has been a trend to move away from infrastructure based systems towards more autonomous, vehicle based systems. It is too early in the development of these applications to determine what final form they will take, but an appropriate mix of infrastructure and vehicle based systems will likely occur that may incorporate radionavigation services.

Railroads have been conducting tests of GPS and differential GPS since the mid-1980s to determine the requirements for train and maintenance operations. In June 1995, FRA published its report, *"Differential GPS: An Aid to Positive Train Control,"* (Ref. 9) which concluded that differential GPS could satisfy the Location Determination System requirements for the next generation positive train control systems. In November 1996, FRA convened a technical symposium on *"GPS and its Applications to Railroad Operations"* to continue the dialogue on accuracy, reliability, and security requirements for railroads.

Integrity requirements for land transportation functions are dependent on specific implementation schemes. Integrity values will probably range between 1 and 15 seconds, depending on the function. In order to meet this integrity value, GPS will most likely not be the sole source of positioning. It will be combined with map matching, dead reckoning, and other systems to form an integrated approach, ensuring sufficient accuracy, integrity, and availability of the navigation and position solution to meet user needs. Integrity needs for rail use are 5 seconds for most functions. Those for transit are under study and are not available at this time. The availability requirement for highways and transit is estimated as 99.7 percent. The availability requirement for rail is estimated as 99.9 percent.

Table 2-7. Land Transportation Positioning/Navigation System Accuracy Needs/Requirements

MODE	ACCURACY (meters) 95%
Highways:	
Navigation and route guidance	5-20
Automated vehicle monitoring	30
Automated vehicle identification	30
Public safety	10
Resource management	30
Accident or emergency response	30
Collision avoidance	1
Geophysical survey	5
Geodetic control	< 1
Rail:	
Train control	2
Transit:	
Vehicle command and control	30-50
Automated voice bus stop annunciation	5*
Emergency response	75-100
Data collection	5

* *25-30 meters before the bus stop.*

While the Government has no statutory responsibility to provide radionavigation services for land radionavigation applications or for non-navigation uses, their existence and requirements are recognized in the Federal radionavigation systems planning process. Accordingly, the Government will attempt to accommodate the requirements of such users.

2.6 Requirements for Non-Navigation Applications

The use of radionavigation systems, especially GPS, for non-navigation applications is very large and quite diverse. Most of these applications can be grouped under the following five broad headings:

- Geodesy and surveying
- Mapping, charting, and geographic information systems (GIS)
- Geophysical applications
- Meteorological applications
- Timing and frequency

The nature of these applications is discussed in sections 2.6.1 through 2.6.5 below.

2.6.1 Geodesy and Surveying

Since the mid-1980s, the geodesy and surveying community has made extensive use of GPS for worldwide positioning. Today, GPS is used almost exclusively by the geodesy and surveying community to establish geodetic reference networks. The National Geodetic Survey (NGS) currently uses GPS to provide the Federal component of the National Spatial Reference System (NSRS) through the establishment of a small number of monumented points (about 1200) positioned using GPS, and the provision of GPS observations from a nationwide GPS network of Continuously Operating Reference Stations (CORS) for use in post processing applications. The CORS system currently provides data over the Internet from 144 stations, including the USCG stations and U.S. Army Corps of Engineers (USACE) stations. Stations to be established by components of DOT to support air navigation (e.g., WAAS) and land navigation (e.g., NDGPS) will be included in CORS as they become available.

GPS is used extensively in a large number of surveying applications. These include positioning of points in support of reference system densification, mapping control, cadastral surveys, engineering projects, and terrain mapping. These applications involve both positioning of fixed points and after-the-fact positioning of moving receivers using kinematic methodologies. All high-accuracy (few centimeter) geodetic and surveying activities involve DGPS techniques using the carrier phase observable.

2.6.2 Mapping, Charting and Geographic Information Systems (GIS)

GPS technology is extensively used to provide positions of elements used to construct maps, charts, and GIS products. These have many applications, including supporting air, sea, and land navigation. Almost all positioning in this category is DGPS positioning and involves the use of both code range and carrier phase observations, either independently or in combination. Many groups at all government levels, as well as universities and private industry, have established fixed reference stations to support these applications. Most of these stations are designed to support after-the-fact reduction of code range data to support positioning at the few decimeter to few meter accuracy level. Examples of this type of positioning application include 1) location of roads by continuous positioning of the vehicle as it traverses the roads, and 2) location of specific object types such as manhole covers by occupying their locations. Another very important mapping/GIS application of GPS is post mission determination of the position and/or attitude of photogrammetric aircraft. For this application, code range or carrier phase data are used depending upon the accuracy required. The use of GPS for this purpose is so cost effective that it is becoming the preferred method of positioning photogrammetric aircraft.

2.6.3 Geophysical Applications

The ability of GPS carrier phase observations to provide centimeter level differential positioning on regional and worldwide bases has lead to extensive applications to support the measurement of motions of the Earth's surface associated with such phenomena as motions of the Earth's tectonic plates, seismic (earthquake related) motions, and motions induced by volcanic activity, glacial rebound, and subsidence due to fluid (such as water or oil) withdrawal. The geodetic and geophysical communities have developed an extensive worldwide infrastructure to support their high accuracy positioning activities.

The geophysical community is moving rapidly from post processing to real-time applications. In southern California and throughout Japan, GPS station networks currently transmit data in real time to a central data facility to support earthquake analysis. The International GPS Service for Geodynamics (IGS) is moving to provide the ability to compute satellite orbit information, satellite clock error, and ionospheric corrections in real time. Many projects for the monitoring of motion are currently being supported by the National Science Foundation (NSF), the U.S. Geological Survey, and NASA, as well as state, regional, and local agencies.

Another geophysical application is the determination of the position, velocity, and acceleration of moving platforms carrying geophysical instrumentation both to determine the position of measurements and to provide a means of computing measurement corrections. An example of this is the use of GPS in conjunction with an aircraft carrying a gravimeter. Here, GPS is used not only to determine the position of measurements but also to estimate the velocity and acceleration necessary for corrections to the observations. GPS position measurements are also being used extensively to monitor motions of glaciers and ice sheets.

2.6.4 Meteorological Applications

The international meteorological community launches three quarters of a million to a million weather radiosondes and dropwindsondes each year worldwide to measure such atmospheric parameters as pressure, temperature, humidity, and wind speed and direction. Currently Loran-C, Radio Direction Finding and recently GPS are methods used for weather instrument tracking. With the loss of the Omega system, which had been widely used by the international community for tracking weather radiosondes, and the projected phaseout of Loran-C, there has been a concerted effort to use GPS technology for tracking and wind speed and direction determination. GPS-based upper-air systems will be in wide use early in the next millennium. Measurements of refraction of the two GPS carrier phases can be used to provide continuous estimates of total precipitable water vapor. The ability to provide accurate water vapor information has been demonstrated in the research mode. Development of research meteorological GPS station networks has begun.

2.6.5 Time and Frequency Applications

GPS and Loran-C are being used extensively for communication network synchronization by, for example, telephone companies. Power companies are using GPS for measuring phase differences between power transmission stations, for event recording, for post disturbance analysis, and for measuring the relative frequency of power stations. GPS is also being used for worldwide time transfer. Another timing application of GPS is synchronization of clocks to support astronomical observations such as Very Long Baseline Interferometry (VLBI)/pulsar astronomical observations.

2.6.6 Summary of Requirements

Almost all non-navigation uses of GPS involving positioning have accuracy requirements that necessitate differential positioning and therefore augmentation through the use of one or more reference stations located at point(s) of known position. The accuracy requirements for various applications are indicated in Table 2-8 and lie in the few millimeter to few meter range. Non-navigation requirements differ from navigation requirements in several respects. Many non-navigation applications do not have real-time requirements and can achieve their objectives through post processing of observations. This reduces communications needs and means that reliability and integrity requirements are much less stringent. Even when real-time applications exist the penalties for data loss are usually economic rather than related to safety of life and property considerations. However, non-navigation uses have much more stringent accuracy requirements in many cases.

There are several consequences of these accuracy requirements. First, the carrier phase observable is used in many non-navigation applications rather than the code range observable, which is the primary observable used on most navigation applications. Second, two carrier phase frequencies are essential to achieve the few millimeter to few centimeter accuracies needed for many applications. Dual frequency carrier phase capability is also required for recovery of precipitable water vapor information in support of meteorological applications. The non-navigation GPS user community has developed an extensive worldwide augmentation infrastructure to support their applications. Under the auspices of the International Association of Geodesy (IAG), the IGS has been established. The IGS operates a worldwide network of GPS stations. Data from these stations are used to produce high accuracy (better than 10 cm) orbits and to define a worldwide reference coordinate system accurate at the 1 cm level. Currently, the high accuracy orbits are produced a few days after the fact. However, slightly less accurate orbits are being produced with less than 24 hour delay and IGS members are rapidly moving toward this production of real-time orbits at the few decimeter level. Member groups of the IGS are also moving toward the production of satellite clock corrections and ionospheric corrections in real time.

In addition to these integrated worldwide efforts many groups at national, state, and local levels have or are in the process of establishing networks of GPS reference stations. The bulk of these station networks now in existence provide observational data that can be used to compute correction information needed to perform code range positioning at the few decimeter to few meter level. Increasingly, reference station networks that provide both carrier phase and code range observations are being introduced. Almost all of these reference station networks support post processing at present, but many state groups are looking toward providing code range correctors in real time. The nature of GPS reference station requirements of non-navigation users is cost as well as accuracy driven. Thus, where real-time code range positioning is not required and user equipment cannot receive real-time correctors it may be more cost effective to perform post processing rather than upgrade equipment. Also, if user equipment and software is designed to use local area DGPS correctors, as is currently the case for most non-navigation users employing code range positioning, it is cost effective to continue to use local area DGPS if possible. With high accuracy carrier phase positioning in areas such as surveying, minimizing the observation time required to achieve a given accuracy is an important cost consideration. Thus, observation time minimization may result in a need for GPS reference stations at intervals of 40 to 200 km to meet carrier phase positioning requirements.

Table 2-8. Requirements for Surveying, Timing and Other Applications

Surveying

TASK	MINIMUM PERFORMANCE CRITERIA								REMARKS
	ACCURACY - 1 SIGMA				COVERAGE %	AVAILABILITY %	INTERVAL		
	POSITION						MEASUREMENT RECORDING (seconds)	SOLUTION FIX	
	ABSOLUTE (m)		RELATIVE (cm)						
	HORIZONTAL	VERTICAL	HORIZONTAL	VERTICAL					
Static Survey	0.3	0.5	1.0	2.0	99	99	5	30 min	0 - 25 km
Geodetic Survey	0.1	0.2	1.0	2.0	99	99	5	4 hr	0 - 6000 km
Rapid Survey	0.3	0.5	2.0	5.0	99	99	1	5 min	0 - 20 km
"On The Fly" Kinematic Survey	0.3	0.5	2.0	5.0	99	99	0.1 - 1.0	0.1 - 1.0 sec	0 - 20 km Real Time
Hydrographic Survey			300	15	99	99	1	1 sec	

Timing and Other Applications

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS								
	ACCURACY (2 drms)			COVERAGE	AVAILABILITY	FIX INTERVAL	FIX DIMENSION	SYSTEM CAPACITY	AMBIGUITY
	PREDICTABLE	REPEATABLE	RELATIVE						
Communications Network Synchronization	-	1 part in 10^{-10} (freq)*	-	Nationwide	99.7%	Continuous	N/A	Unlimited	N/A
Scientific Community	-	1 part in 10^{-10} (freq)	-	Worldwide	99.7%	Continuous	N/A	Unlimited	N/A
Meteorology	Velocity 1m/sec	-	-	-	TBD	TBD	TBD	-	TBD
Power Network Synchronization	-	1ms**	-	North America	99.7%	1 second	Two	Unlimited	Resolvable with 99.9% confidence

* Proposed ITU Standard based on American Telephone and Telegraph "Stratum 1 Requirement."

** At any substation. 8ms (1/2 cycle) systemwide.

Geophysical users have special references station requirements in that they are using fixed stations to monitor motions and must place reference stations at spacings and at locations that allow them to monitor the motions of interest. Organizations such as USACE have positioning requirements for hydrographic surveys to locate waterway channels, construction and obstructions. Meeting these requirements necessitates the establishment of DGPS stations along inland waterways.

2.7 Military Radionavigation Requirements

Military forces must be prepared to conduct operations anywhere in the world, in the air, on and under the sea, on land, and in space. During peacetime, military platforms must conform to applicable national and international rules in controlled airspace, on the high seas, and in coastal areas. Military planning must also consider operations in hostile environments.

2.7.1 General Requirements

Military navigation systems should have the following characteristics:

- Worldwide coverage.
- User-passivity.
- Capability of denying use to the enemy.
- Support of unlimited number of users.
- Resistance to deception (e.g., spoofing), interference, intrusion or jamming.
- Resistance to natural disturbances and hostile attacks.

- Effectiveness of real-time response.
- Availability for combined military operations with allies.
- Are accommodated in appropriate radionavigation bands.
- Use of common grid for all users.
- Position accuracy that is not degraded by changes in altitude for air and land forces or by time of year or time of day.
- Accuracy when the user is in high "G" or other violent maneuvers.
- Maintainable by operating level personnel.
- Continuous availability for fix information.
- Non-dependence on externally generated signals.
- Provides method for ensuring system integrity, to include an annunciation system to alert users when the system should not be used.
- Continuously reliable for navigation.

The ideal military positioning/navigation system should be totally self-contained so that military platforms are capable of performing all missions without reliance on information from outside sources. No single system or combination of systems currently in existence meets all of the approved military navigation requirements. No known system can provide a common grid for all users and at the same time be passive, self-contained, and yield the worldwide accuracies required. The nature of military operations requires that essential navigation services be available, with the highest possible confidence that these services will equal or exceed mission requirements. This, among other considerations, necessitates a variety of navigation techniques and redundant installations on the various weapon system platforms for military operations. Currently, the DOD is unable to conduct some military missions with the precision and accuracy demanded without some aid from external radionavigation systems. However, there has been significant progress in the development of reliable self-contained systems (inertial systems, Doppler systems, geomagnetic navigation, and terrain/bottom contour matching).

DOD must invest in reliable, accurate, self-contained systems that are uniquely tailored to match platform mission requirements. Therefore, the DOD Positioning, Navigation, and Timing (PNT) architecture will be based upon GPS, which provides accurate worldwide positioning, velocity and time, backed by modern, accurate, and dependable self-contained systems.

2.7.2 Service Requirements

Service and Defense agencies' PNT requirements are validated in accordance with a Joint Chiefs of Staff instruction. Validated requirements are reflected in the Chairman of the Joint Chiefs of Staff Master Positioning, Navigation, and Timing Plan (CJCS MPNTP). The CJCS MPNTP provides the policy and planning bases for all military PNT requirements, compares requirements to existing technology, identifies performance shortfalls, highlights needed research and development, and provides long-term projection of anticipated capabilities.